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Optical Interface Assembly for TOW Trainer

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ABSTRACT

The Software Engineering Directorate constructed a target acquisition training module that replaces the tactical target acquisition head attached to a TOW missile launcher. Soldiers can train on this tactical simulator without expending costly munitions. The module contains a large LCD panel upon which real time scenery, moving targets, and scene movements (coordinated with launcher pointing) are presented to the gunner trainee via the standard TOW tactical "monocular" eyepiece. This paper discusses the design and prototyping of the *optical interface assembly* that connects the LCD to the gunner's tactical eyepiece so that the trainee sees a realistic presentation. A mandatory constraint dictated that only off-the-shelf optics be employed for the prototype. A half-wave retarder is also incorporated in the beam path to alleviate polarization effects. The completed system met the design specifications, cost, and schedule constraints. It also provides a practical (and digestible) example of the optical engineering art for students embarking on this career path.

1. Introduction

In an effort to provide cost effective training to soldiers responsible for operational use of the Army's various tactical missile systems, the Software Engineering Directorate at Redstone Arsenal is developing various Basic Skills Trainers (BSTs). These BSTs must retain the "touch and feel" of the real tactical systems. In the case of the Improved Target Acquisition System (ITAS) BST this is accomplished by using much of the TOW missile launcher (as shown in **Figure 1**). The TOW is a tripod or vehicle mounted missile launcher whose primary role is that of a tank killer. Large numbers of these systems are deployed worldwide. The tactical TAS head contains, among other things, the visible & infrared optical sighting systems, and a laser range finder. The use of a TOW BST during training avoids "wear and tear" on the expensive tactical TAS head, and the expenditure of costly munitions.

The TAS training module is about the same size as the actual TAS head, and attaches to the launcher in place of the tactical TAS head. Inside the module is a large (10.1") liquid crystal display (LCD) similar to those on a lap top PC. The LCD presents to the gunner trainee digital pictures of real scenery (like the missile range at Ft. Benning) in both far infrared and full color visible. The digital pictures are processed to determine the distance of every pixel from the gunner's position. Targets are superimposed on the scene, and they move around the scene in patterns that are designed for each training scenario, and can be modified indefinitely by a "path editor". The gunner's pointing movements are finely tracked by two fiber optic gyroscopes, and the scene moves in response to the pointing.

The TAS training module makes use of the same tactical eyepiece as used on the real TAS head. It is through this tactical eyepiece that the gunner views a target scene. However, a critical component for the successful operation of the ITAS BST is the *optical interface assembly* which connects scenes displayed on the LCD to the gunner via the tactical eyepiece. In real life the target may be a thousand yards away, but in the training module the target shown on the LCD is about a foot away. Consequently, the *optical interface assembly* must be designed such that the target presentation has a 'real world' feel to it. This paper discusses the design, construction and testing of a prototype *optical interface assembly* developed for the ITAS BST.

2. Problem Definition

Figure 2 shows a replica of the actual sight housing (indicated in Figure 1) used to develop the trainer. The LCD, motion sensing gyros, and interface optics are to be contained in this box-like structure. The large (7" x 6") LCD panel can be seen in Figure 2 toward the back interior of the box. The tactical eyepiece (essentially a telescope with binocular eyepiece) is attached externally as indicated in the figure. **Figure 3** is a top-view illustrating the envelope constraint, and the additional complication of a 3.5" lateral offset between the center of the LCD panel and the optical axis of the tactical eyepiece.

An optical interface had to be designed for a short object conjugate and a large FOV. The beam emerging from the interface had to be collimated so that the LCD would appear to be at infinity when viewed through the tactical eyepiece. An optical layout of the tactical eyepiece is shown in **Figure 4.** The stop is a 0.79" diameter aperture sitting about a half inch in front of the telescope objective - a singlet. The light from the objective is then split into two paths (via various fold mirrors and beam-splitters) to feed the binocular eyepieces. (Only one eyepiece path is shown in Figure 4.)

The interface optics were to be "invisible" in the sense that they would mimic the actual system and not noticeably degrade the image quality observed by the trainee through the tactical eyepiece. Keeping distortion low was a particular concern. Aside from these constraints, an additional requirement specified the use of commercially available, inexpensive, off-the-shelf optics. All these conditions made the interface optics design an interesting challenge.

3. Design Approach

The light emerging from the optical interface assembly had to be <u>collimated</u> for the tactical eyepiece. So the first thing was to estimate the focal length needed by the interface optics. There was enough information laying about to do this. The LCD was 6" x 7", therefore, the distance from the center to the corner of the display is $y_D = 4.6$". Also known was the focal length of the telescope objective: $f_T = 3.747$", and that its image height was $y_T = 0.55$". Referring to **Figure 5,** it is easy to see that:

$$y_T / f_T \; = \; y_D / f_D \qquad\qquad (1)$$

Solving for f_D :
$$f_D = \; (y_D / y_T) f_T. \qquad\qquad (2)$$

Inserting the known values:
$$f_D = \; (4.6" / 0.55") 3.747" $$

$$\mathbf{f_D = 31.34"} \qquad\qquad (3)$$

Since length of the box interior is only 16.75", use of a single lens (whether singlet or achromat) was ruled out in this tight space.

4. Telephoto Design (First Order)

A design concept that might work given the length constraint is a telephoto lens[1,2] used in reverse. The telephoto can provide a long effective focal length in a short space. Consequently, the goal of this section is to determine the powers (focal lengths) of the front and back components of the telephoto that will fit the constraints of the problem.

The standard telephoto equations will be used at this point to help determine a viable first order design. The power of the positive element is given by:

$$f_P = t\, f\, /\, [(1 - \kappa)\, f + t]. \qquad\qquad (1)$$

where t is the separation between components; κ is the telephoto ratio; and f is the <u>system</u> focal length.

The power of the negative element is given by:

$$f_N = [\,(f_P - t)\,(\kappa f - t)\,]\, /\, (f_P - \kappa f) \qquad\qquad (2)$$

The separation between the two is:

$$t = \tfrac{1}{2}\,(f_P + \kappa f) \qquad\qquad (3)$$

The telephoto ratio is the ratio of the total length, L, of the system (from the positive element to the image plane) to the system focal length. The constraint is that:

$$\kappa = (L\, /\, f) \langle\ 1 \qquad\qquad (4)$$

The distance from the negative element to the image plane is the back focal length (BFL).

$$BFL = \kappa\, f_D - t \qquad\qquad (5)$$

After some trials, the parameter values down-selected are shown in **Table 1**.

Table 1

f	30"
κ	0.5"
L	15"

Equations 1 and 2 then become: $f_P = 30 \, t \, / \, (15 + t)$ $\qquad\qquad$ (6)

$$f_N = (f_P - t)(15 - t) \, / \, (f_P - 15) \qquad\qquad (7)$$

Equations 6 & 7 are plotted over a range of lens separation values in **Figure 6**.

After some more trials, the selected value for lens separation was set at 4". The shorter inter-lens separation pulls the negative element further from the LCD. It also allows this element to have a smaller diameter. The corresponding focal lengths are: $f_P = 6.316"$ and $f_N = -2.934"$. These values were inserted into the Zemax lens design code (using the paraxial lens option). The layout is shown in **Figure 7**. The LCD panel is on the left-hand side. The location of the paraxial lenses (which have zero thickness) are indicated. The light emerging from the stop on the right-hand-side is collimated. So this idealized telephoto does serve its purpose.

5. Telephoto Design Using Real Commercial Lenses

The next step was to search the commercial lens base in Zemax to find positive and negative achromats with focal lengths (and appropriate diameters) close to those found via the first order design. Further, these lenses also had to be in-stock because the goal was to build a prototype quickly! The best compromise is shown in Table 2.

Table 2

	Neg. Element	Pos. Element
Vendor	Edmund Scientific	Melles-Griot
Part No.	J45-222	LAO159
EFL	-3.936"	10.237"
Dia	1"	1.57"

These lenses were inserted into Zemax and the system was optimized (in normal telephoto orientation) for a 30" system EFL by allowing the inter-lens spacing to vary and judiciously flipping the negative element. The resulting parameter values are shown in **Table 3,** which compare well with those in **Table 1**.

Table 3

t	3.68"
f_D	30"
κ	0.51"
L	15.29"

This telephoto <u>as used</u> is shown in **Figure 8.** Note that we are vignetting quite a bit at the negative lens. A plot of the vignetting is shown in **Figure 9**, and the limits of the 100%, 50%, and 25% unvignetted areas are overlayed on top of the LCD boundaries in **Figure 10.** The corners of the screen are, in fact, significantly vignetted. This is an acceptable trade-off, however, since the lens was readily available and the vignetting tends to reduce the distortion measured relative to the spot centroids.

6. Incorporation of Folded Path

Recall from Figure 3 that there is a 3.5" lateral offset between the center of the LCD display and the optical axis of the tactical eyepiece. This meant that a pair of 90^0 fold mirrors had to be somehow incorporated into the optical interface design. Placing such a folded path between the LCD and the telephoto meant larger mirrors (and larger mounts). There really was no room for these because of the electronics that also took up much of the limited space inside the box. Nor was there room to put a fold mirror pair after the telephoto because the stop had to be 1" from the positive lens. The solution was to place one fold mirror at 45^0 within the telephoto (between the positive and negative elements), and a second fold was placed immediately after the positive element. A right angle prism was used in internal reflection here to provide a little extra optical path. This folded path telephoto is shown in **Figure 11.** This interface optical system fits nicely within the box envelope box with some axial room to spare.

7. Mount Design and Assembly

Although the optical components used for the optical interface assembly were readily available through commercial sources, the same could not be said for the mounts. These had to be specially designed and fabricated. **Figure 12** shows a 3-D view of the mount assembly. It consists of five major components: two lens mounts; two prism platforms; an L-shaped support bracket. The latter bolts directly to the side of the sight-housing. The bracket supports the component mounts such that the interface optical system axis is centered on the aperture stop and coincident with the optical axis of the telescope assembly. The support bracket is machined from quarter inch thick aluminum stock. It has slots for axial translation of the lens mounts. The bracket has pins to center the prism platforms which also allow some azimuth rotation for alignment purposes. The negative lens mount is designed so that it can move axially in the front bracket slot without incurring any rotation misalignment. The width of this mount is the same as the lens edge thickness so that there is no vignetting due to the mount. The positive lens mount also has some axial adjustment capability, but in practice butts up snugly against the second prism platform. Both the negative and positive achromats are held in place in their respective mounts via side set screws. Each prism platform has a small machined-out step at 45^0. This allows the prism to be accurately positioned onto the platforms. The prisms themselves are attached to the platforms with RTV. Once properly positioned, all component mounts are locked in place via bolts.

The optical interface was assembled and aligned on an external test fixture. Focus adjustments were made on the lenses. Then by tilting the prism near the aperture stop, the centration of the pupil in the eyepiece could be adjusted. By tilting the prism near the negative lens, the centration of the image in the pupil could be adjusted. After allowing time for the RTV to set and then re-verifying alignment, the whole assembly is integrated into the sight housing box. The LCD image was then viewed through the tactical eyepiece. The image was crisp and there was no perceptible distortion. There was some minor clipping of the display corners due to vignetting by the negative lens, but this was expected. The clear aperture of the commercially available lens was not quite big enough.

8. Polarization Effects

There were two unexpected problems. The first was pinkish and purplish streaks running across the image. They were not on the display when viewed directly, nor when the display was viewed through the system without the tactical eyepiece in place. This appeared to be a polarization effect. However, this problem disappeared when the customer reached into the box and pealed off a protective plastic sheet from the front of the display! The second problem (after removal of the protective sheet) was a very large and objectionable difference in display brightness when it was viewed separately through each eyepiece of the binocular. This turned out to be a polarization sensitivity issue.

The LCD output is itself linearly polarized, essentially at a 45 degree angle relative to the horizontal plane. Light from the display proceeds through the interface optical system with its two prisms. Prisms are known to create different amounts of di-attenuation and retardance (both in magnitude and orientation) as a function of incidence angle. This applies to both coated and uncoated prisms. So the polarization structure of the light leaving the interface optics is somewhat different than what went in. But the real problem occurs in the tactical eyepiece. Prisms are used here to split the light into two paths. But the splitting is done in an asymmetric manner. So the polarizance along the two paths is also asymmetric. This results in a net change in brightness level for light emerging from the right and left eyepieces respectively.

Fortunately this problem had a simple and cost-effective solution. A plastic half-wave retarder was placed directly in front of the negative lens. The attachment to the lens mount was such that the retarder could be rotated about the system optical axis. An observer would view the display brightness through the optical interface assembly/tactical eyepiece. The retarder would be rotated as the observer watched the brightness balance shift between the right and left eyepieces. A rotation position for the retarder was found such that there was no perceptible difference seen between the right and left views of the display. At this point, the retarder was fixed in place with locking clips.

9. Discussion

The ability to train large numbers of soldiers on missile launchers using actual equipment modified with interactive software to simulate target acquisition, missile launch, and target negation is a practical and cost-effective approach when dealing with expensive munitions. The ITAS system discussed here is but one example of a growing and successful trend. However, in order to provide a 'seamless' experience for the trainee when using standard launch platforms, the optical sighting hardware must be modified so that the computer-generated scene presented on the LCD appears to be at the proper object conjugate. Consequently, the optical interface assembly which connects the display to the tactical eyepiece plays a critical role in the overall success of this training method. As seen in the example presented here, the optical interface assembly can present some interesting and unique design and implementation challenges.
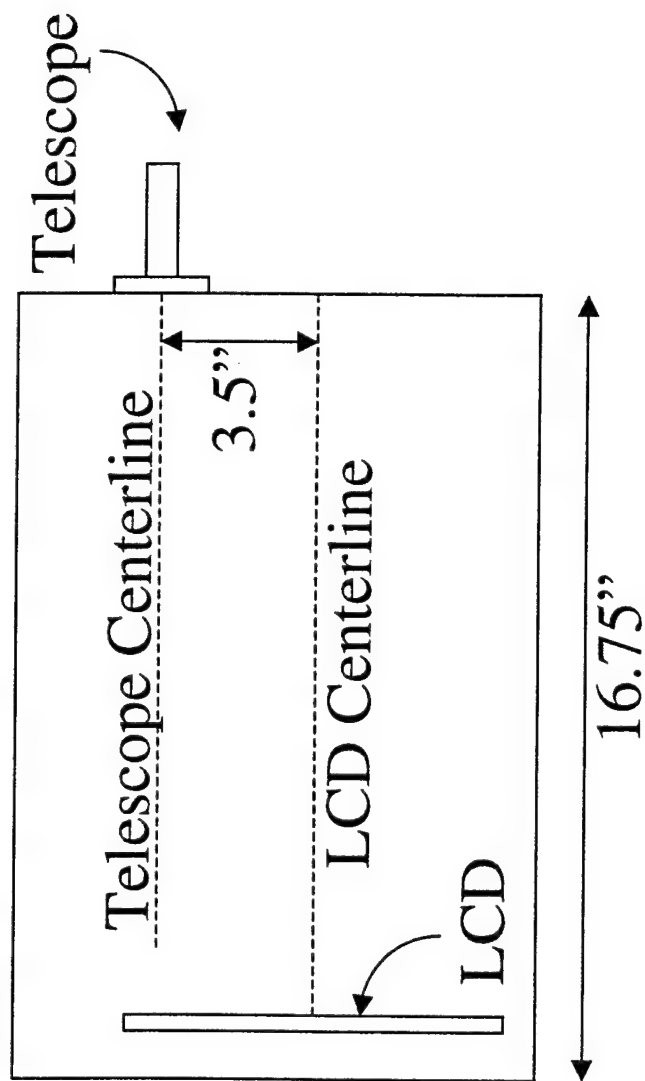
This optical interface problem also provides a perfect example for beginning students in optical systems engineering. The problem and the constraints are real, but not overly complex. Schedule, cost, and performance must all be weighed to design a sufficient system, and real world surprises must be analyzed, diagnosed, and accommodated quickly and efficiently. This is what is expected of optical engineers.
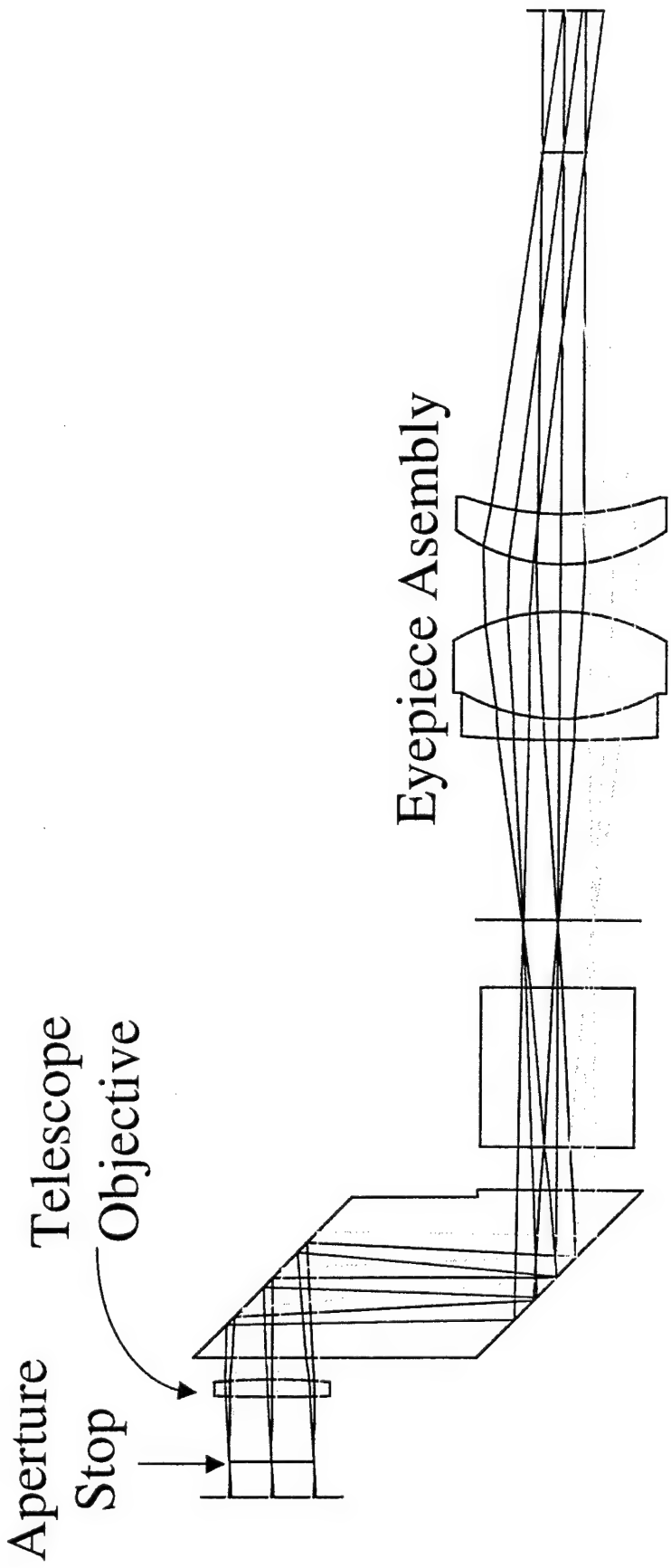
10. References

1) R. Kingslake, "Lens Design Fundamentals", Chapter 13, Academic Press (1978).

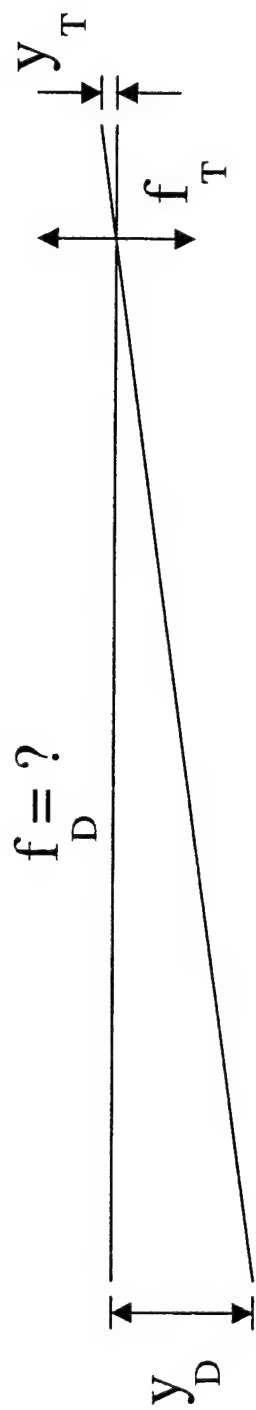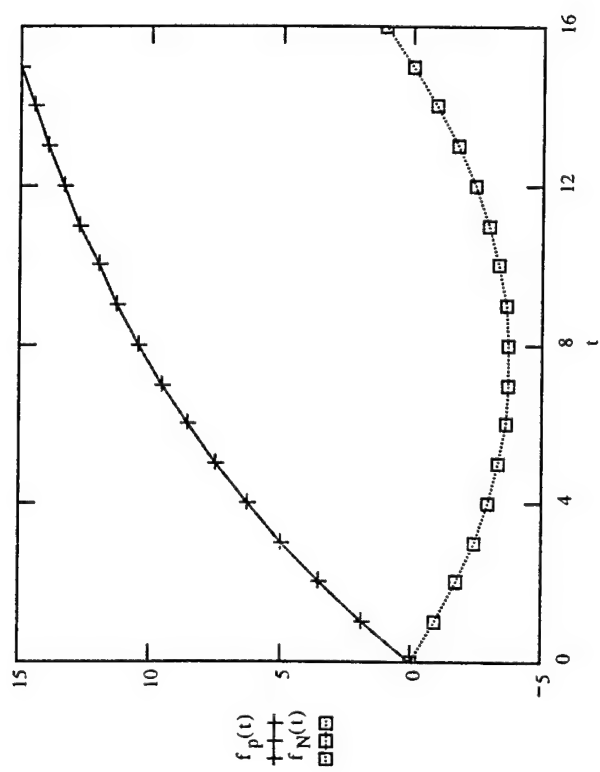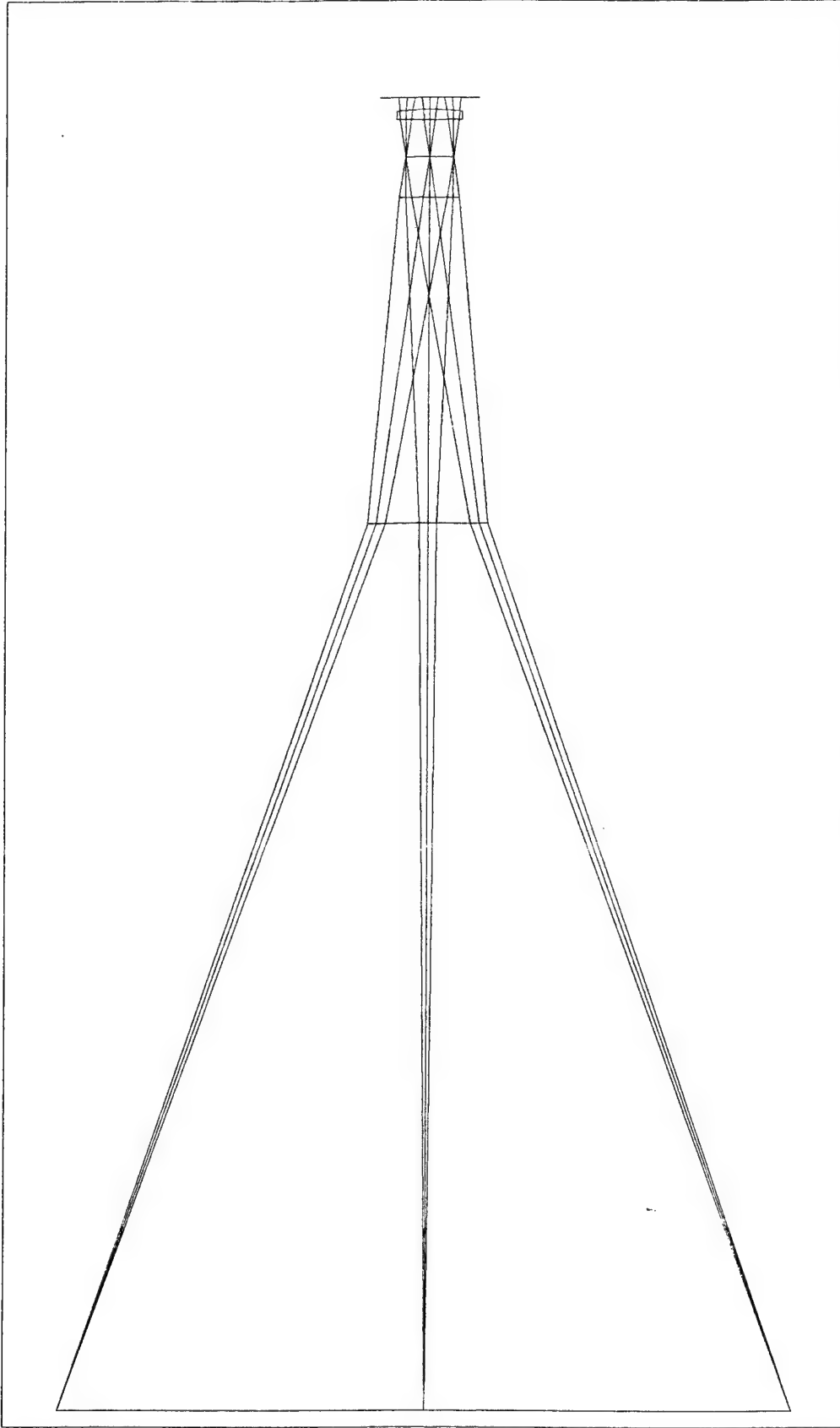2) J. Geary, "Introductiion to Lens Design", Chapter 36, Willmann-Bell (2002).

Telescope

Telescope Centerline

3.5"

LCD Centerline

LCD

16.75"

Aperture Stop

Telescope Objective
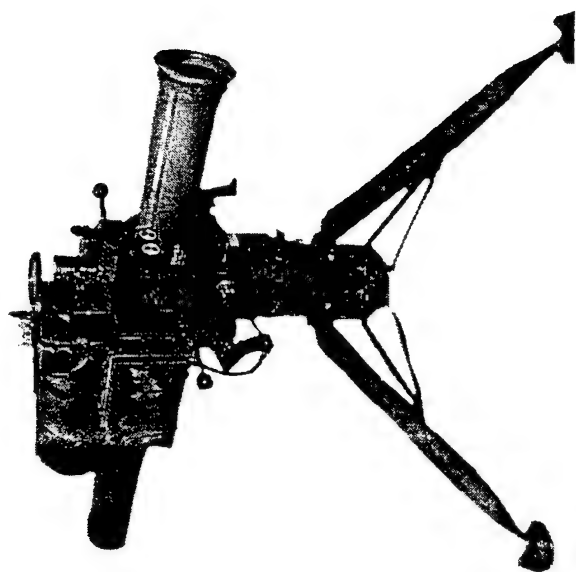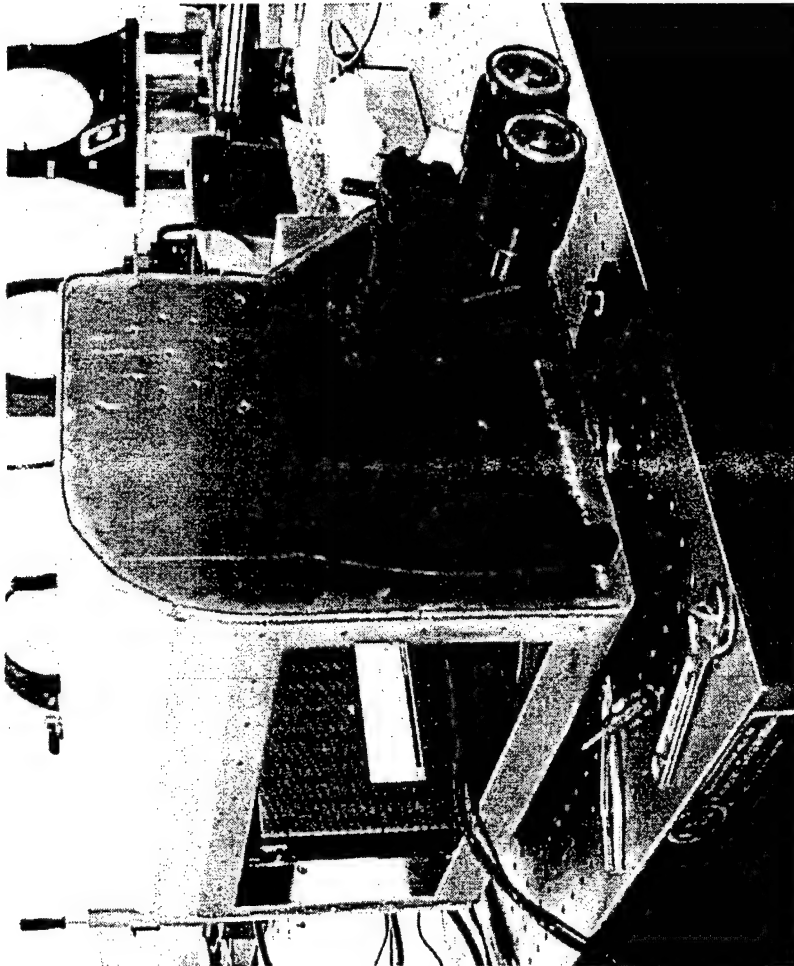
Eyepiece Asembly

3D LAYOUT

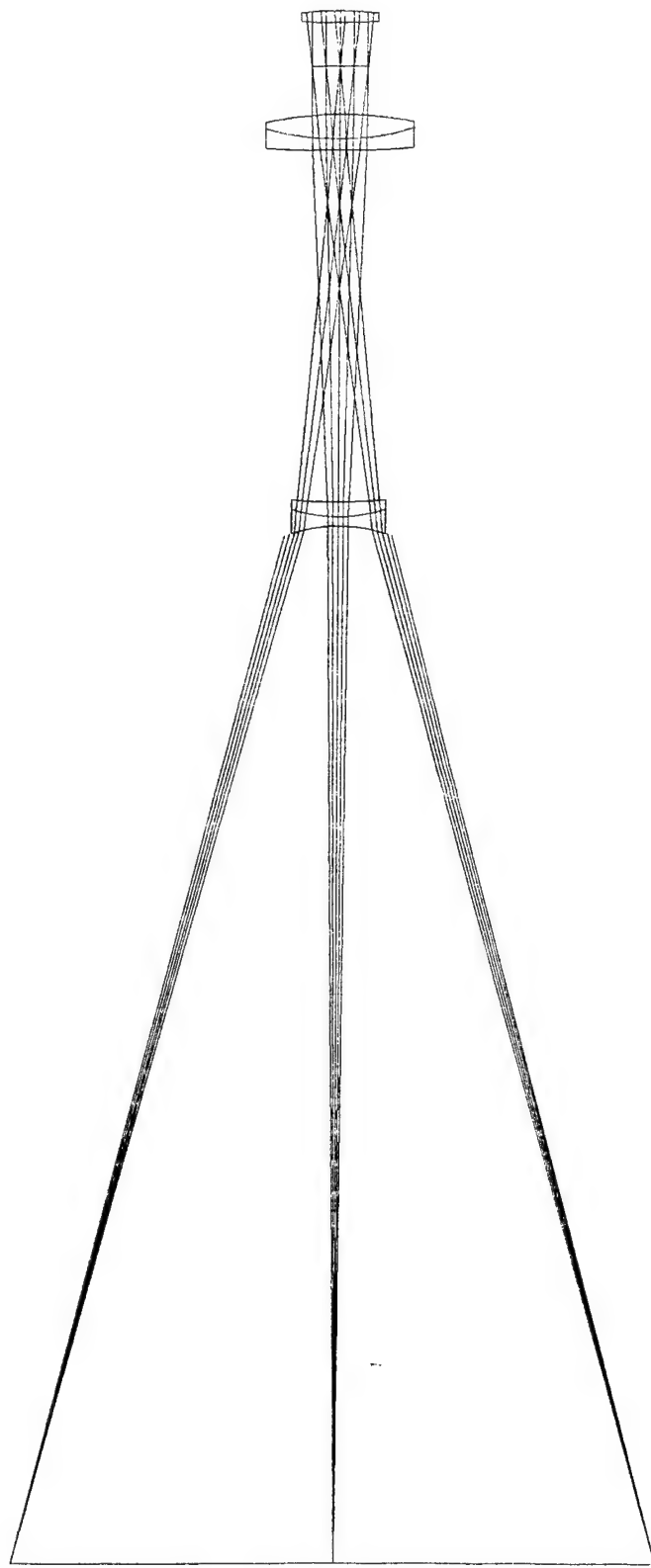ITAS TELESCOPE ASSEMBLY
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$$f_D = ?$$

$$y_T$$

$$f_T$$

$$y_D$$

3D LAYOUT

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ARMY EYEPIECE
THU JUN 7 2001
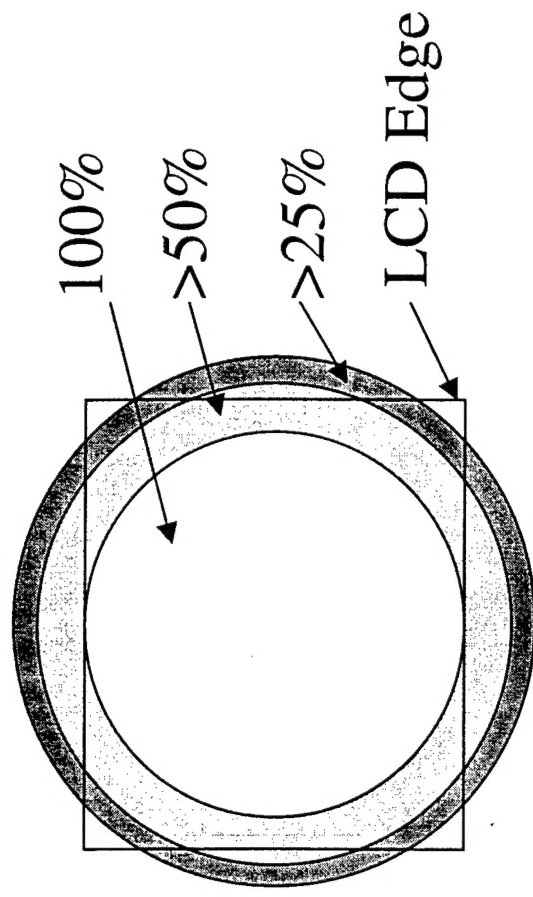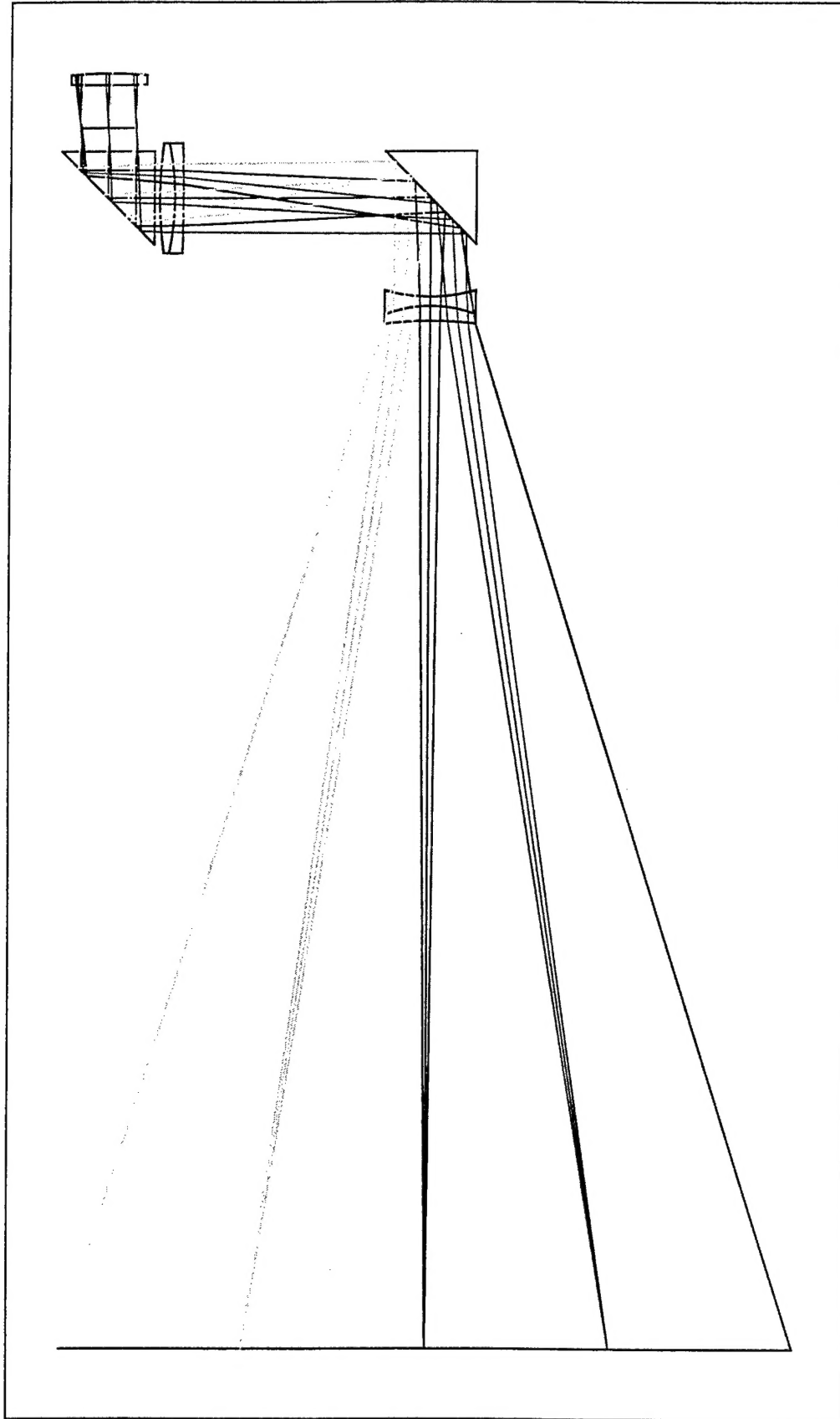SCALE: 0.5000

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VIGNETTING DIAGRAM

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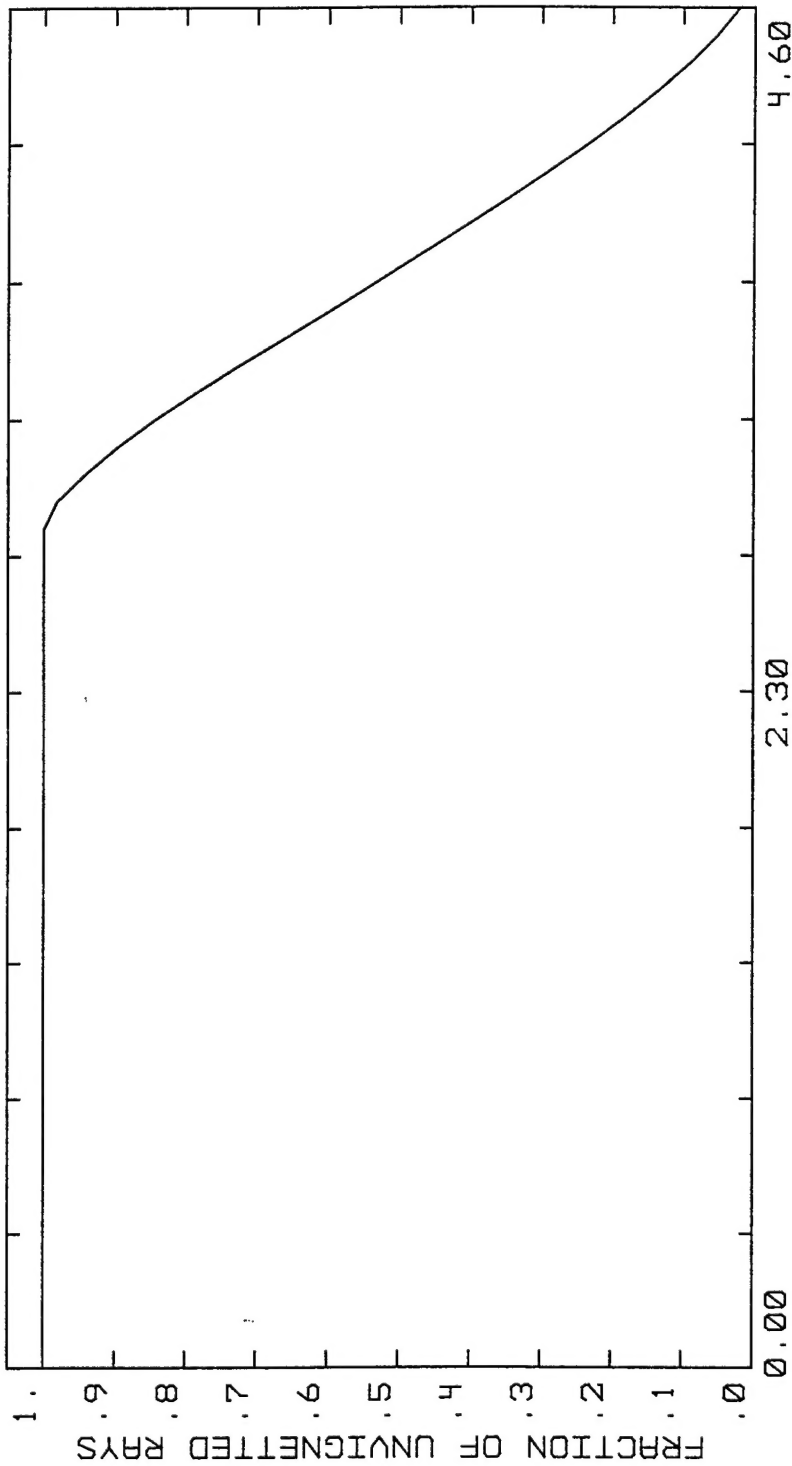
ITAS REAL LENS TELEPHOTO
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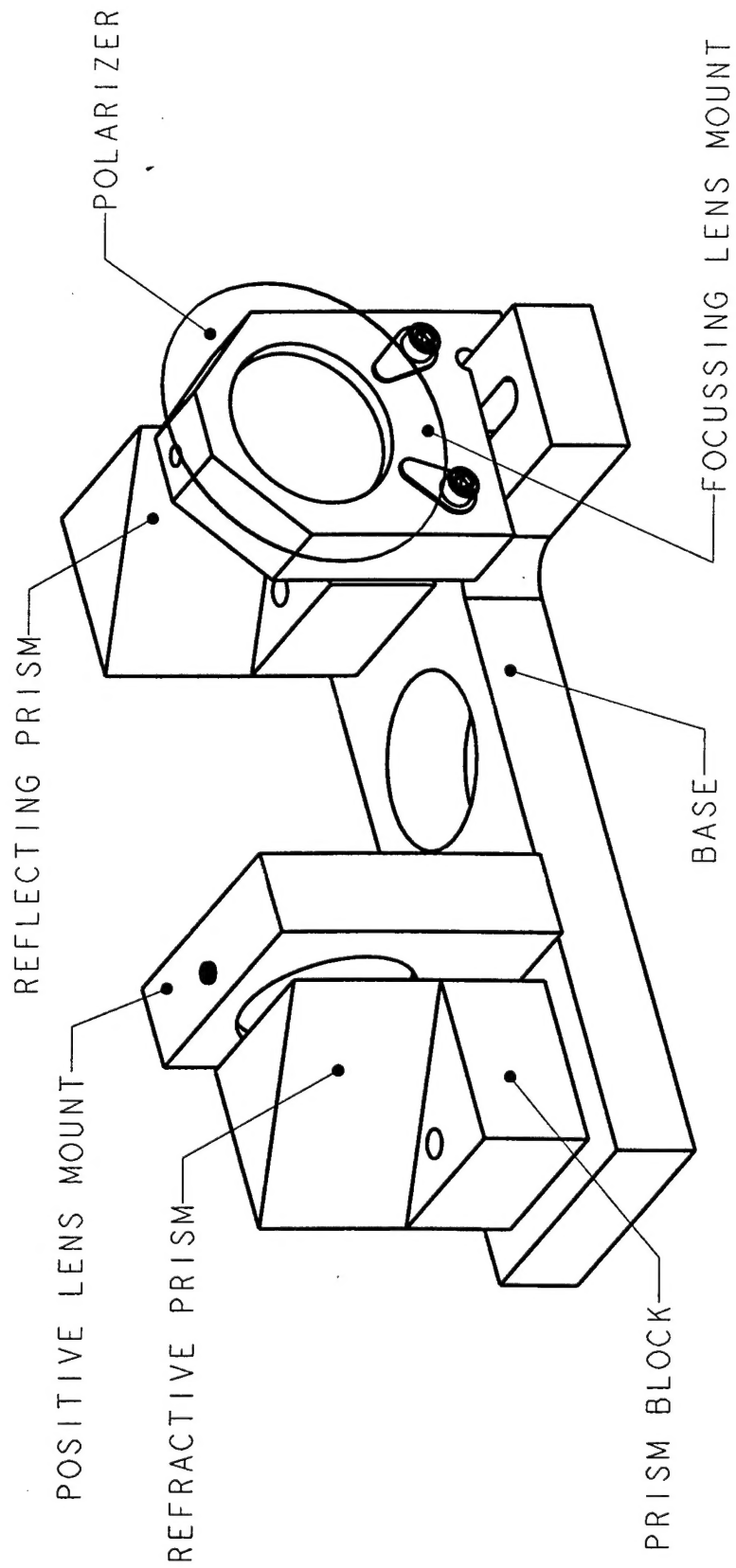CONFIGURATION 1 OF 1

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LCD Edge

Fraction of Unvignetted Rays

3D LAYOUT

ITAS FOLDED TELEPHOTO
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CONFIGURATION 1 OF 1

POLARIZER

FOCUSSING LENS MOUNT

REFLECTING PRISM

BASE

POSITIVE LENS MOUNT

REFRACTIVE PRISM

PRISM BLOCK

SCALE 1/1

USA-AMCOM
SIMULATOR SIGHT
ASSEMBLY

UAH_A

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